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AD

VARIATION OF MECHANICAL PROPERTIES IN LARGE STEEL FORGINGS

U.S. ARMY ARMAMENT COMMAND

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

APRIL 1975

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In a continuing effort to determine the causes of mechanical property variation in large steel forgings, the effects of forging reduction on mechanical and metallurgical properties were examined. The related work previously conducted at Watervliet has been appropriately summarized in a recent report, WVT-TR-74001.

The present study deals specifically with the metallurgical consequences of solidification and mechanical working. Accordingly, the aspects of

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nonmetallic inclusions, chemical homogeneity and microstructure were considered.

For the range of forging reductions investigated (1.5:1 - 10:1), a reduction ratio of approximately 3:1 produced optimum average values in % RA, Charpy impact strength and fracture toughness. Also, the significant variations statistically determined in these parameters was accompanied by real variation in carbon concentration. Therefore, carbon segregation on a macroscale, is shown to be a major contributor to mechanical property variation in large steel forgings.

WVT-TR-75019

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GLOSSARY

ANOVA	Analysis of Variance
σ^2	Variance (universe)
S^2	Estimate of variance
F	Ratio of mean square in question to error mean square
S.S.	Sum of squares
M.S.	Mean Square
YS	Yield Strength (ksi)
UTS	Ultimate Tensile Strength (ksi)
El	Elongation (%)
RA	Reduction of Area (%)
Cv	Charpy Impact (ft-lb)
K_{I_C}	Plane Strain Fracture Toughness (Mode I Loading)
K_5	Fracture Toughness (at 5% Secant)
D.F.	Degrees of Freedom

INTRODUCTION

The variations encountered in mechanical properties of large steel forgings have been a particularly troublesome problem for many years. These aberrations are frequently responsible for high rejection rates, and also contribute to the failure of structural components throughout a broad spectrum of the steel making and steel fabricating industry.

As early as 1918, Georges Charpy[1] concluded that the amount of deformation undergone at high temperature by a block of steel affects the properties of the metal according to a complex law which involves the initial stage of the ingot and all the subsequent deformations. The chief characteristic of the deformation is to create strongly marked heterogeneity. Moreover, he states that general rules are impossible to apply to all forgings. For components operating under applied transverse stresses, such as guns, longitudinal forging has an undoubtedly injurious effect upon mechanical properties required for performance.

Post World War II studies of the transverse mechanical properties in heat treated wrought steel products by Wells and Mehl[2] demonstrated that variation of quality (measured by Reduction in Area) within solid forgings or tubes was much higher than generally recognized. A maximum to minimum difference among 250 values for specimens taken from a single forging was rarely less than 18% (RA), e.g., 30% RA minimum and 48% RA maximum. Frequently, the differences amounted to 30% RA and occasionally 40% RA or higher.

1. Charpy, G., The Iron Age, April 24, 1919, p. 1079.
2. Wells, C. and Mehl, R.F., Trans. ASM, vol. 41, 1949, p. 715.

Appropriately enough, they also concluded that comparable size tubes from a similar position in ingots cast from a single heat, usually have about the same transverse RA quality. The quality of tubes coming from the bottom thirds of ingots is generally slightly lower and occasionally much lower than that of tubes coming from the middle or top thirds of ingots. The implication drawn from this determination is that solidification of the "primary casting" can affect the final properties of the finished forging. Furthermore, these investigations concluded that elongated nonmetallic inclusions and the heterogeneous distribution of chemical elements in solution are together largely responsible for the transverse ductility of forgings being lower than longitudinal ductility.

More recently, several studies have been primarily concerned with the variations in mechanical properties of low alloy steel forgings. The significant findings of the first investigation (conducted on 38 gun tubes) demonstrated that tensile ductility, Charpy impact energy and fracture toughness (pre-cracked Charpy) varied considerably within a single tube, within a disc from that tube, within a vendor's practice and from vendor to vendor[3]. Following this sweeping revelation, another study attempted to determine the level and reproducibility of mechanical properties in present gun tube material, quenched to a uniform microstructure of 100% martensite and tempered to yield strength ranges of 140-160 ksi and 160-180 ksi[4]. The most important fact disclosed by this

3. Slawsky, M.L., Heiser, F.A. and Liuzzi, L., "The Variation of Mechanical Properties in 175mm M113 Gun Tubes", Watervliet Arsenal Technical Report, WVT-6734, July 1967.

4. Baldrey, D. and Lyons, T., "Variation in Mechanical Properties of Tempered Martensite Gun Steel", WVT-7020, March 1970.

work was that the variation in mechanical properties (excluding yield strength), found in the reheat treated test specimens was controlled by some factor in the manufacturing process other than heat treatment.

Another recent investigation statistically analyzed the mechanical property data from 9 full size gun tube forgings by an Analysis of Variance technique (ANOVA)[5]. Two of the conclusions are particularly pertinent:

1) The percent RA attained in forgings of equivalent configuration showed significant variation when the forgings resulted from different ingot positions. Conversely, the % RA attained in similar forgings exhibited insignificant variation when the forgings came from similar ingot positions. This demonstrated the effect of solidification parameters on variation of mechanical properties in large forgings.

2) Also, significant variation was found in yield strength and room temperature Charpy impact energy for similar forgings produced from identical size ingots but different heats of steel, illustrating the effect of melting variables upon the mechanical properties of the forgings.

Therefore, the object of our present examination was to evaluate the effect of forging reduction on the mechanical properties of low alloy, heavy, steel forgings. The analysis was conducted from both a statistical and metallurgical standpoint. Consequently, significant variation in mechanical properties can be defined and the material parameters that accompany these variations determined.

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5. Thornton, P.A., "On the Variation in Mechanical Properties of Large Caliber Gun Tube Forgings", WVT-7260, Oct. 1972.

THEORY

When two or more independent sources of variation operate, the resulting variance is the sum of the separate variances.[6] The two types of errors which arise, when estimating the property of a bulk material are:

1. Errors of sampling (variance denoted by σ_1^2)
2. Errors of analysis (variance denoted by σ_0^2)

These sources of error operate independently and the total variation may be obtained by the addition of the two.

In order to separate and estimate the variances due to testing and sampling an Analysis of Variance (ANOVA) can be conducted with the experimental data. The ANOVA is essentially a method of separating the variance to which a response (test measurement) is subject, into its various components corresponding to the sources of variation which can be identified. The details of this method can be briefly summarized as follows:

Suppose there are k samples (disks) and n repeat analyses on each, giving a total number of analyses $N = kn$. The analytical error is responsible for the variation in the repeat analyses on each sample, and its variance is denoted by σ_o^2. This variance is estimated by:

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6. Davies, O.L., Statistical Methods in Research and Production, Oliver and Boyd, London, 1961, p. 100

$$\frac{\text{TOTAL of the sums of squares about the sample means}}{\text{TOTAL of the degrees of freedom}} = \sum_{i=1}^{k} \sum_{J=1}^{n} \frac{(x_{ij}-\bar{x}_i)^2}{k(n-1)}$$

where x_{ij} - individual responses (within disks)

$\bar{x}_i$ - disk mean

Similarly, the sampling error variance denoted by $\sigma 1^2$ is estimated by:

$$n \sum_{i=1}^{k} (\bar{x}_i - \bar{x})^2 / (k-1)$$

where $\bar{x}_i$ - disk mean

$\bar{x}$ - grand mean

The sums of squares and degrees of freedom "between disks","within disks" and "total" may be set out in tabular form called the ANOVA table as below:

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Quantity Estimated by Mean Square
Between disks	$n\sum_{i=1}^{k} (\bar{x}_i-\bar{x})^2 = S1$	k-1	S1/(k-1)	$\sigma o^2 = n \sigma 1^2$
Within disks	$\sum_{i=1}^{kn} \sum_{j=1}^{n}(x_{ij}-\bar{x}_i)^2=So$	k(n-1)	So/k(n-1)	σo^2
Total	$\sum_{i=1}^{k} \sum_{j=1}^{n} (x_{ij}-\bar{x})^2$	nk-1		

The results of the Analysis of Variance can then be tested for significance. This is accomplished by setting up the Null Hypothesis that there is no disk to disk variation ($S_1^2 = 0$). Consequently, two independent estimates of S_0^2 are realized; one from the mean square within disks, and the other from the mean square between disks. To test whether these two estimates differ significantly, i.e., whether they differ by more than can be reasonably explained on the grounds of errors in the estimates, the ratio of the mean square between disks to the mean square within disks is calculated. This ratio (F) is the measure of the variation caused by the effect divided by the variation due to repeat tests. The resultant F value is then compared with a table of variance ratio for the respective degrees of freedom, and a particular significance level. A significant value of F_{calc} ($F_{calc} > F$ table) discredits the Null hypothesis and it can be concluded that real variations exist in the property under consideration, from disk to disk.

PROCEDURE

In order to evaluate the effects of forging on mechanical property variation, two identical ingots were poured from the same heat of vacuum degassed, low alloy steel (4335 modified with V). The heat (22 tons) was melted in a basic electric-arc furnace. Ingot dimensions are given in Figure 1. The ingots were then forged into stepped-down cylinders to achieve the desired forging reductions as illustrated in Figure 2. All tests were taken in the transverse orientation, which is equivalent to the C-R orientation according to ASTM E399. The sampling plan is shown in Figures 3 and 4. The following expression was employed in a reiterative manner to arrive at a satisfactory sample size:

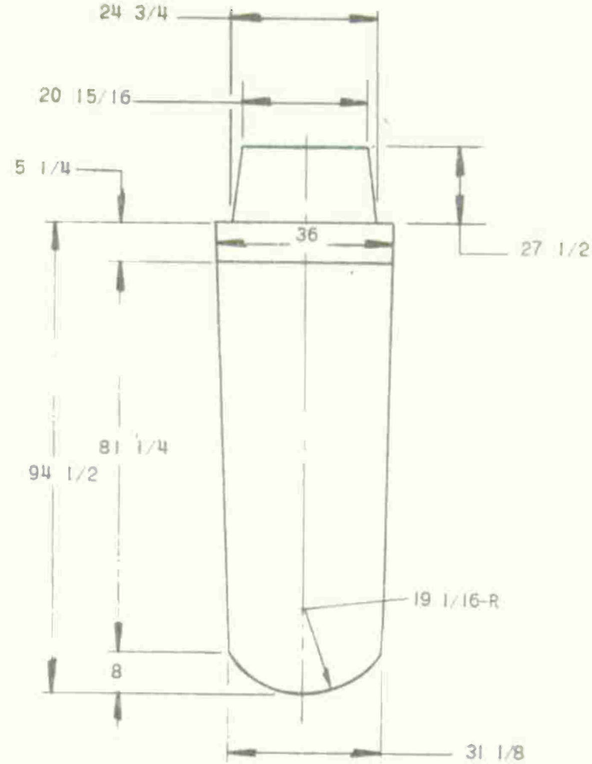

Fig. 1 - Schematic showing ingot dimensions.

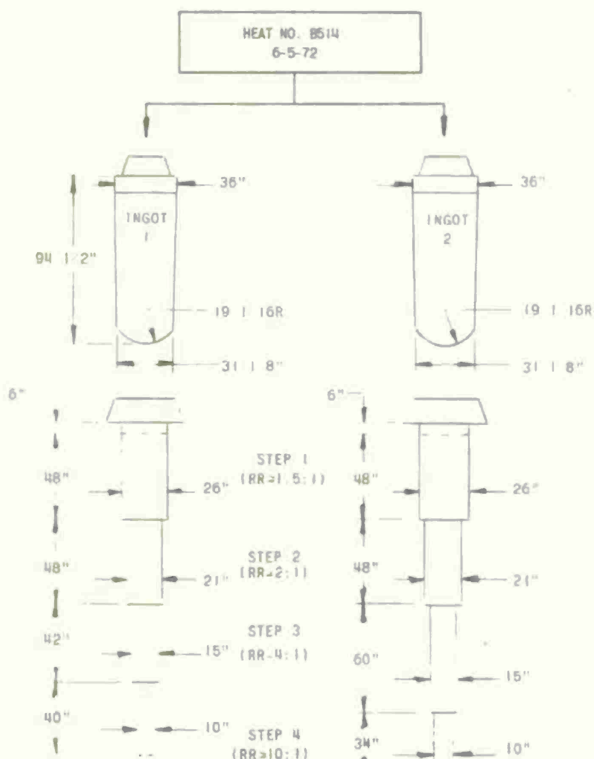

Fig. 2 - Schematic illustrating stepped cylindrical forgings.

$$t_{\phi}(\alpha) = \frac{(\bar{x} - \mu)}{S/n^{1/2}}$$

where: t - probability point $\begin{cases} \alpha \text{ - probability} \\ n - 1 = \phi \text{ degrees of freedom} \end{cases}$

$\bar{x}$ - sample mean (background)

μ - population grand mean (background)

$(\bar{x} - \mu)$ - error

S - sample std. deviation (background)

n - sample size required

The mechanical property data was statistically analyzed by the Analysis of Variance technique to define any variations that may exist. This analysis included yield strength, % RA, Charpy impact and fracture toughness.

Correspondingly, a metallurgical analysis consisting of microstructure, chemistry and non-metallic inclusion assessment, was conducted to determine the material parameters responsible for the mechanical behavior and any attendant variation in the data. In regards to the non-metallic inclusion content, a two-dimensional systematic point count was employed according to Hilliard and Cahn.[7] This analysis is based on the principle that the fractional number of randomly or regularly dispersed points falling within the boundaries of a two-dimensional feature on a plane, provides an unbiased estimate of the volume fraction of the feature.

It should be noted that heat treatment of the steel was carried out on the test specimen blanks, prior to finish machining, rather than the entire forgings themselves. This allowed much closer control of the microstructure and produced a tempered martensite structure in all specimens thereby essentially eliminating heat treatment as a variable.

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7. Hilliard, J.E. and Cahn, J.W., Trans, AIME, 221, p.344, 1961

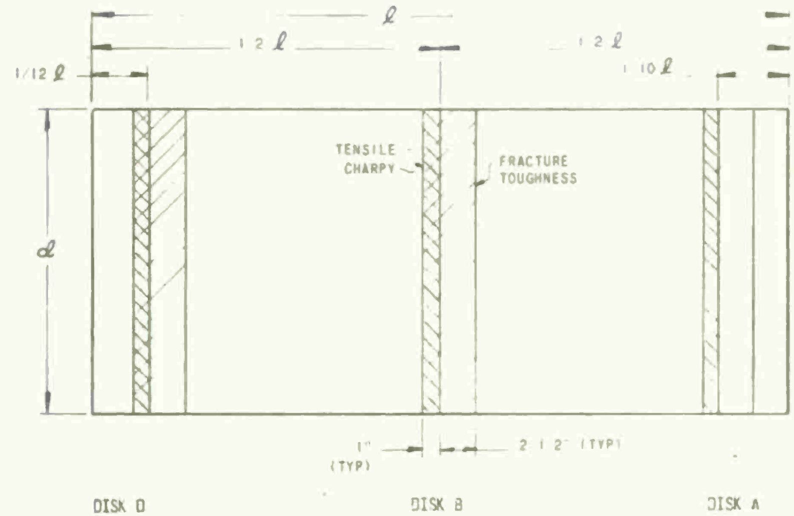

Fig. 3 - General sampling layout of disks within a step.

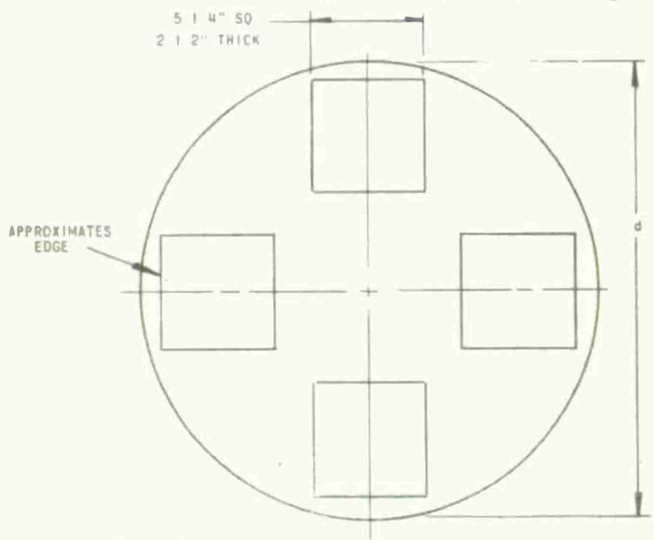

Fig. 4a. - Tensile and Charpy specimen layout within a disk.

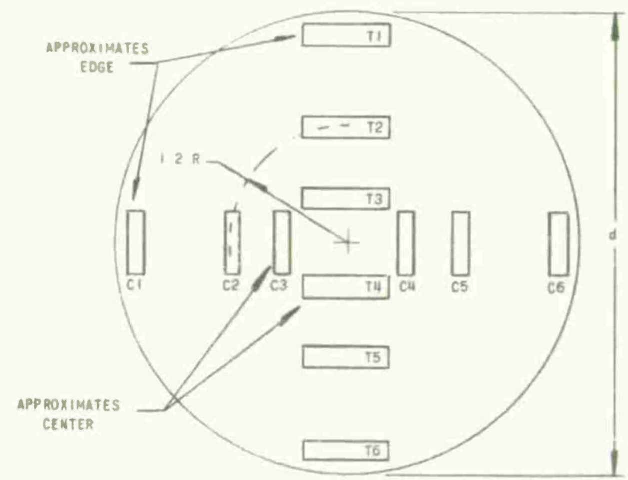

Fig. 4b. - Layout of fracture toughness specimens within a disk.

RESULTS AND DISCUSSION

Mechanical:

The results of the mechanical property tests, which include 144 tensile, 144 Charpy impact and 60 compact tension fracture toughness specimens are tabulated in Appendices A to C. Since yield strength, % reduction of area, Charpy impact energy and fracture toughness are widely accepted indicators of a steel's ability to perform in service, we employed them in the statistical analysis portion of this investigation. Accordingly, the same parameters will be addressed in the overall discussion of mechanical behavior.

The results of the Analysis of Variance on the mechanical properties are given in Tables 1-4. This information is summarized for the 5% significance level in Table 5. The summary shows that the degree of forging reduction (steps) is responsible for significant variation in all the properties under consideration. No significant variance was evidenced among disks and only one parameter out of four, Charpy impact, demonstrated significant variation due to separate ingots. Figures 5-12 display the properties under consideration for both ingots. The plots show the mean values for each disk and also the respective maximum and minimum values. The yield strength (0.1% offest) for both step forgings ranged from approximately 170-180 ksi. Unfortunately, the specimens from Step 4's were heat treated separately from the remaining test specimens (Steps 1-3) and incurred yield strengths in the lower portion of this range. Therefore, the trend of decreased yield strength for this

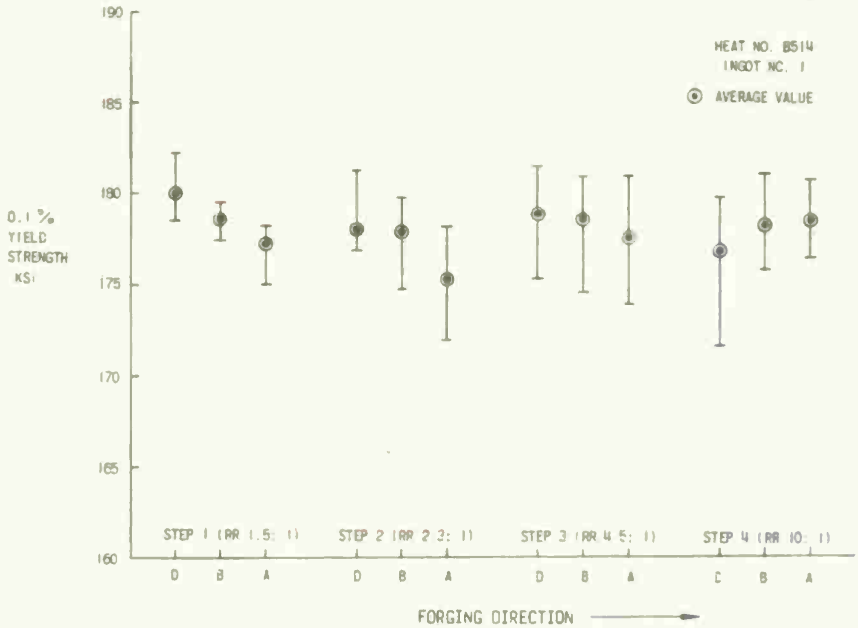

Fig. 5 - Variation of Yield Strength with forging reduction in Ingot No. 1.

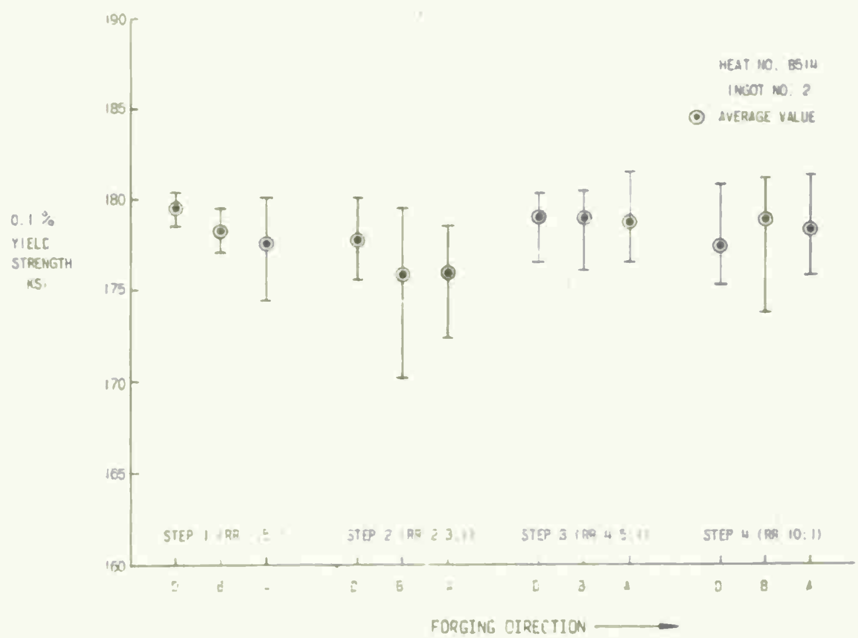

Fig. 6 - Variation of Yield Strength with forging reduction in Ingot No. 2.

step does not reflect the consequences of forging reduction alone. Occasionally, small inconsistencies in the heat treating operation, viz., furnace temperature fluctuation, time, placement or position within the furnace, etc., manifest themselves in discrepancies in the yield strength of a material. It appears that this was the case in Step 4. However, since we were also concerned with property variation within disks and between ingots, this data was included in the analysis.

Reduction of area for both step forgings displayed a peaking type of trend with a maximum between 2:1 and 5:1 forging reduction. This effect is shown in Figures 7 and 8. Very noteworthy was the spread within disks at the lower end of the forging reduction scale. Differences as much as 37% RA were observed. There was a distinct tendency for this spread to decrease with greater amounts of forging, but also the average values tended to decrease after a forging reduction of about 4.5:1. This particular phenomena does not coincide with the observations of Wells and Mehl; in the present study the top end of the ingots displayed slightly lower % RA and much greater variation than the middle and bottom portions of the ingots. While the first inclination might be to suspect a deleterious material condition at the top end of the ingots, this may well be a consequence of insufficient working on this portion. This possibility is being investigated by forging sections from the top end of the ingot to the same forging reduction as step 4 (10:1). The results of this evaluation will be reviewed in a future report.

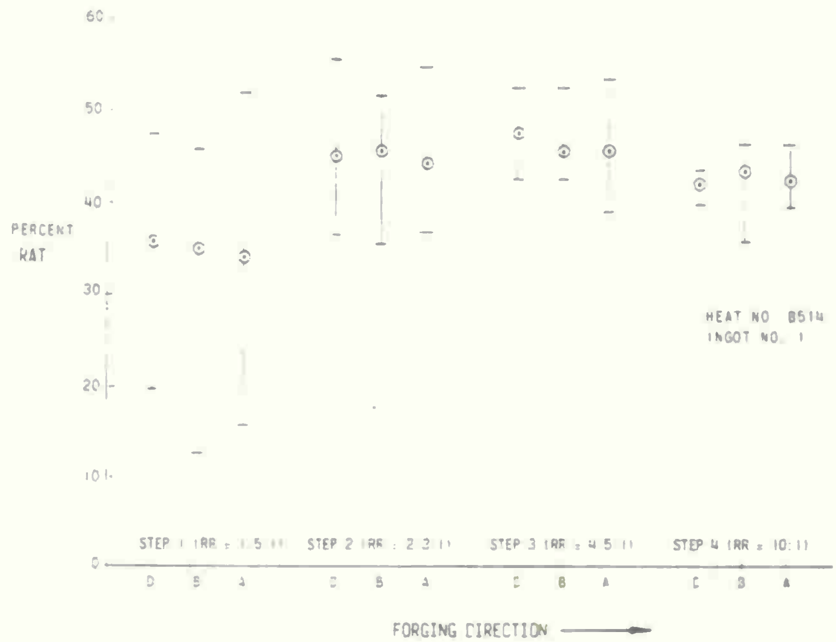

Fig. 7 - Variation of % Reduction of Area with forging reduction in Ingot No. 1.

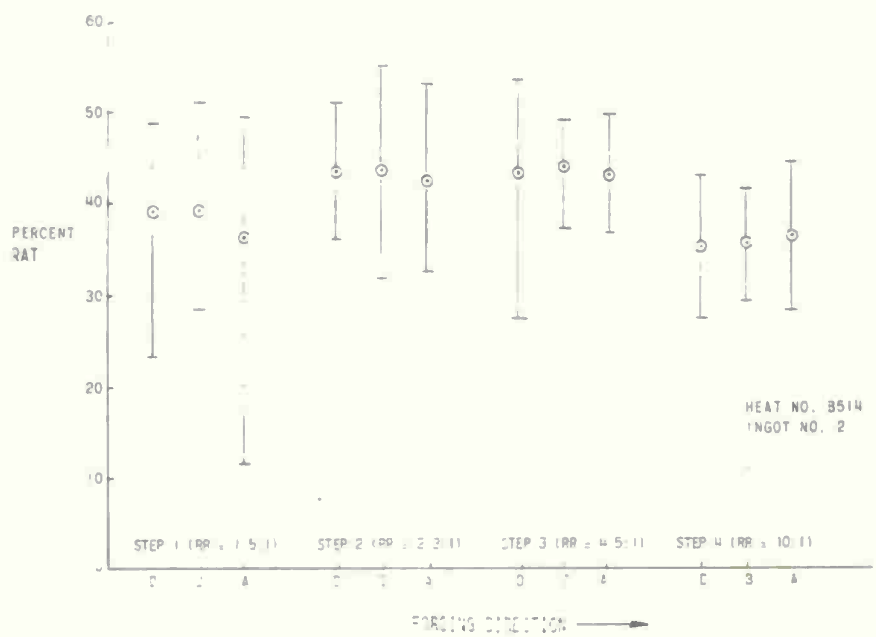

Fig. 8 - Variation of % Reduction of Area with forging reduction in Ingot No. 2.

Initially we anticipated no real mechanical property variation due to identical size ingots. However, the data demonstrates that the same size ingots poured from the same heat can experience variation in Charpy impact behavior. Figures 9 and 10 display the trend in Charpy data with forging reduction. Again we note the peaking type of curve exhibiting slightly higher values in the vicinity of 3:1 forging reduction. However, this trend is upset by the data from both Step 4's. Recalling the inadvertant yield strength increase due to heat treatment, the Charpy impact data, consequently, reflects this deviation. Although, if this discrepancy is examined in light of a general relation developed by Wells and Mehl[8], where impact values are increased on the average by about 3 foot pounds when yield strength is lowered by 5000 psi, our impact data coincides with the trend when corrected.

Therefore, in spite of the fact that these forgings were produced by the same vendor, from identical size ingots, poured from the same heat of steel, real variation was experienced in the Charpy impact energy absorption. If we can assume that the solidification parameters are reasonably similar, then the melting variables such as chemical heterogeneity in the melt, deoxidation and degassing practice, etc., along with tapping and pouring practices, must be responsible for observable variations in properties due to ingots.

8. Wells, C. and Mehl, R.F. Trans. ASM, 41, 1949, p. 803.

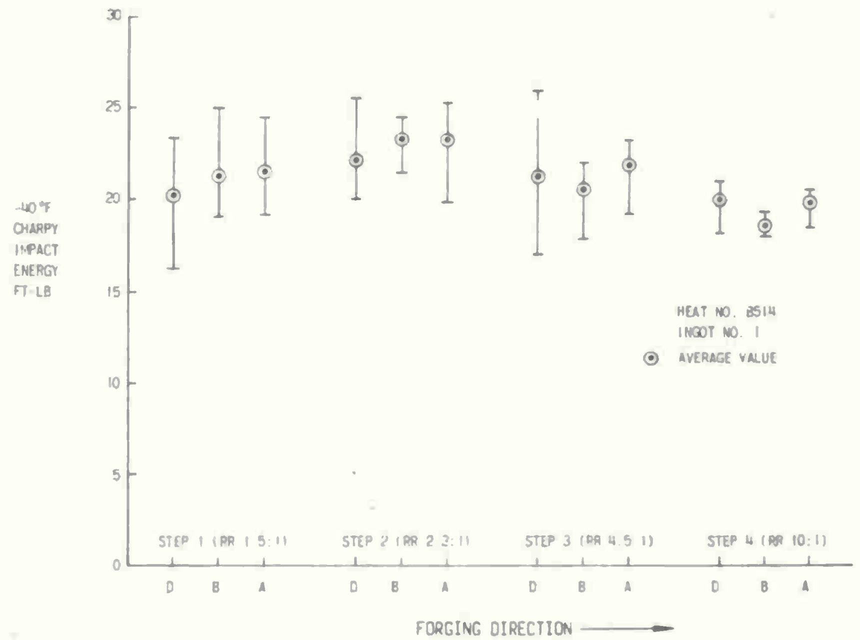

Fig. 9 - Variation of Charpy Impact energy with forging reduction in Ingot No. 1.

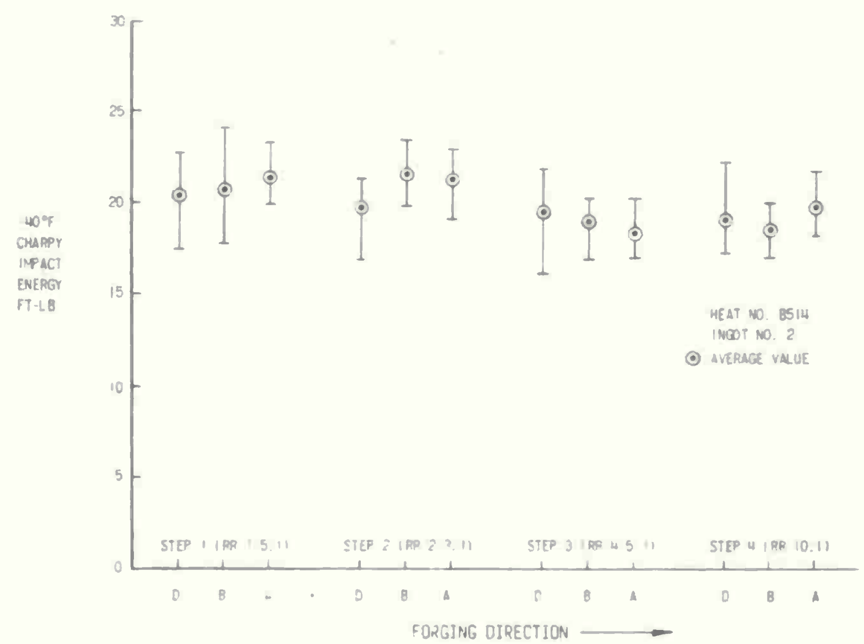

Fig. 10 - Variation of Charpy Impact energy with forging reduction in Ingot No. 2.

Plane strain fracture toughness, as measured according to ASTM E-399, exhibited statistically significant variation due to forging reduction and insignificant variation between ingots and disks within a step. Individual fracture toughness values ranged from 111 ksi-in$^{1/2}$ to 128 ksi-in$^{1/2}$ for a 0.1% yield strength range of 180-188 ksi (0.2% offset yield strength = 186-194 ksi). Average fracture toughness values along with their respective maximum and minimum points are shown in Figures 11 and 12. Analogous to tensile ductility, the fracture toughness of this steel displays a trend for higher average values in the vicinity of 2:1 - 5:1 forging reduction ratio. The stepped forging produced from Ingot 1 shows this behavior much clearer than its counterpart from Ingot 2 and exhibits less spread in data within disks. Although no problem was encountered with the effect of yield strength variations, it must be noted that the data from both Step 4's is subject to some discrepancy because the test specimens were of marginal validity as per ASTM E399. The diameters of Steps 1-3 were large enough to permit specimens of "valid" thickness (2T) while Step 4 permitted 1.6T bars. Our experience with this particular material is that bars of marginal validity will show slightly lower K values (on the order of 5%) than those well within the valid range.

Accordingly, our analysis of variance reflects the data from Steps 1-3. The variation results in Table 4 include the interactions between factors (sources of variation), one of which exhibited marginal variation (between steps). When Step 4 fracture toughness data is included, an additional interaction occurs between the steps and disks.

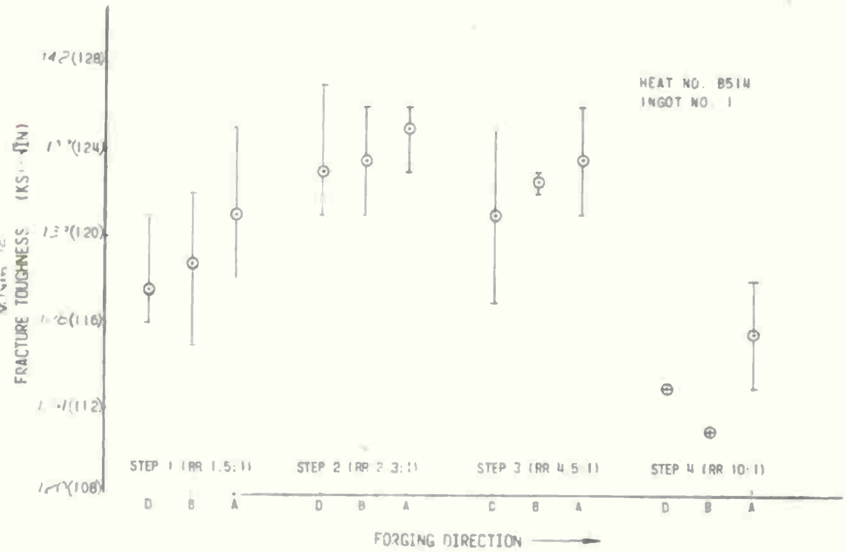

Fig. 11. - Variation of Fracture Toughness with forging reduction in Ingot No. 1.

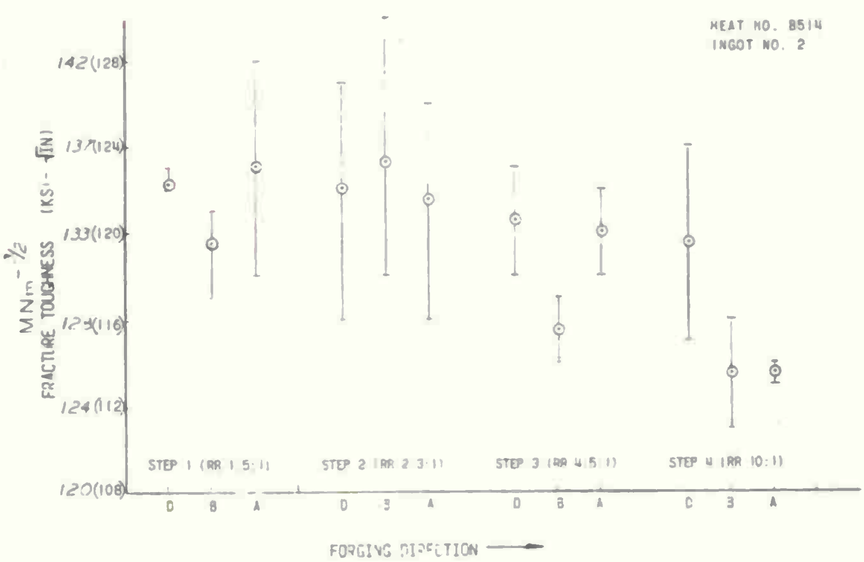

Fig. 12 - Variation of Fracture Toughness with forging reduction in Ingot No. 2.

Therefore, our observations concerning the marginally valid specimens from Step 4(s) appear to be confirmed by the statistical analysis. Furthermore, the introduction of another experimental variable, (specimen size) at this stage of the investigation was not acceptable.

In summarizing the results at this point, Table 5 shows that significant variation was witnessed in all the mechanical properties considered, due to varying forging reduction from 1.5:1 up to 10:1. Based on the literature and our own previous investigations, this outcome was not surprising. Thus, our metallurgical investigation was directed toward the factors that were affected by mechanical working. Two areas were investigated thoroughly, non-metallic inclusion content and chemical homogeneity. Fibering from crystallographic texturing was not considered in this study.

Metallurgical

The evaluation of the non-metallic inclusion content was conducted on two planes in these forgings; transverse and longitudinal (parallel) to the direction of forging. This analysis attempted to detect any sizeable difference in volume percent of inclusions between the two planes. The volume percent estimations are compiled in Table 6. The amount of included matter is relatively low, on the order of 0.05 v/o, well distributed and shows no appreciable difference in the quantity between the two orthogonal planes observed. The general range for both forgings is roughly 0.04 to 0.07 volume percent with the exception of a minimum determination of 0.03 and a maximum determination of 0.08. Inclusion contents on this order are not unusual for this type steel. The inclusion morphology and compositions, viz., globular oxides and silicates, are typical of the nonmetallics obtained in this material. Figure 13 illustrates these inclusions.

Therefore, for the purpose of this analysis, the nonmetallic inclusion content as estimated by volume percent, can be considered relatively constant. In other words, the variation in mechanical properties of the forgings is not the result of variation in the quantity of nonmetallic inclusions. This is not to say that inclusions do not contribute to mechanical property variation but that the observations herein are based on a low, fairly uniform, nonmetallic inclusion level, in the neighborhood of .05% - .07%.

In the area of chemical homogeneity, each disk was analyzed for chemical concentration at seven locations across the diameter. The elements assessed were based on the ladle analysis given as follows:

C	Mn	P	S	Si	Ni	Cr	Mo	V
.35	.38	.010	.010	.21	3.02	.92	.61	.11

Our analyses are tabulated in Appendix D. Based on an examination of the chemistry data, the elements carbon and manganese were subjected to an Analysis of Variance to determine if any significant variation existed in their concentrations throughout the forgings. The other elements analyzed showed no appreciable differences throughout the forgings.

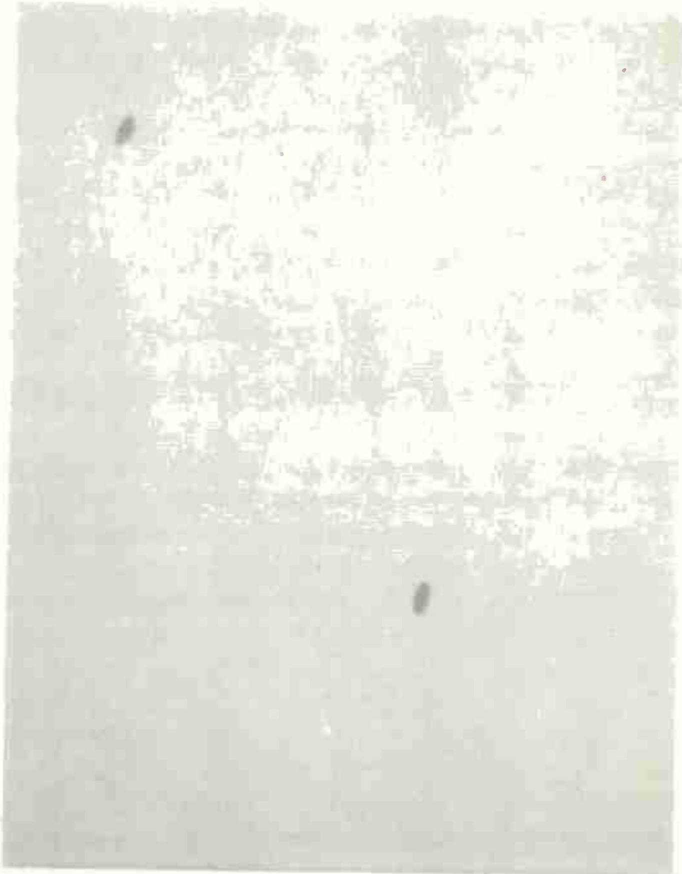

Fig. 13 - Nonmetallic inclusions typical of this material, unetched, 500X.

The ANOVA results for %C and %Mn are displayed in Tables 7 and 8. These data demonstrate that significant variation in carbon concentration was experienced due to separate ingots and steps within an ingot. No real variation in % manganese was displayed due to any of the three factors.

Therefore, considering the apparent variation in carbon distribution in the forgings, Figures 14 and 15 display the average concentration with maximum and minimum values for the seven analyses across each disk. The variation between separate ingots can be observed by comparing the respective average concentrations. For instance, the average carbon concentrations of Ingot 2 are all above the ladle analysis, while those of Ingot 1 range above and below. Likewise, the variation due to steps within ingots is dramatically demonstrated by comparing disk D-Step 2 and disk B-Step 4, in Ingot 2 (Figure 15). The spread in the former being 0.34% to 0.37%, while in the latter case, the range is 0.30% to 0.39%.

This amount of carbon variation is an unfortunate circumstance because the interstitial carbon is fundamental in determining the properties of a steel especially in the heat treated condition[9]. Logically, the more uniform its distribution in the solid, the more uniform are the resultant properties.

Furthermore, the areas chemically analyzed were selected symmetrically, with respect to the center of each disk, on a line from edge to edge. Hence, we have an approximation of the carbon distribution through the forging at those particular cross sections. These profiles are illustrated in Figures 16-23, comparing the % C of respective disks and steps

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9. Bain, E.C. and Paxton, H.W., Alloying Elements in Steel, ASM, Metals Park, Ohio, 1961 p. 127.

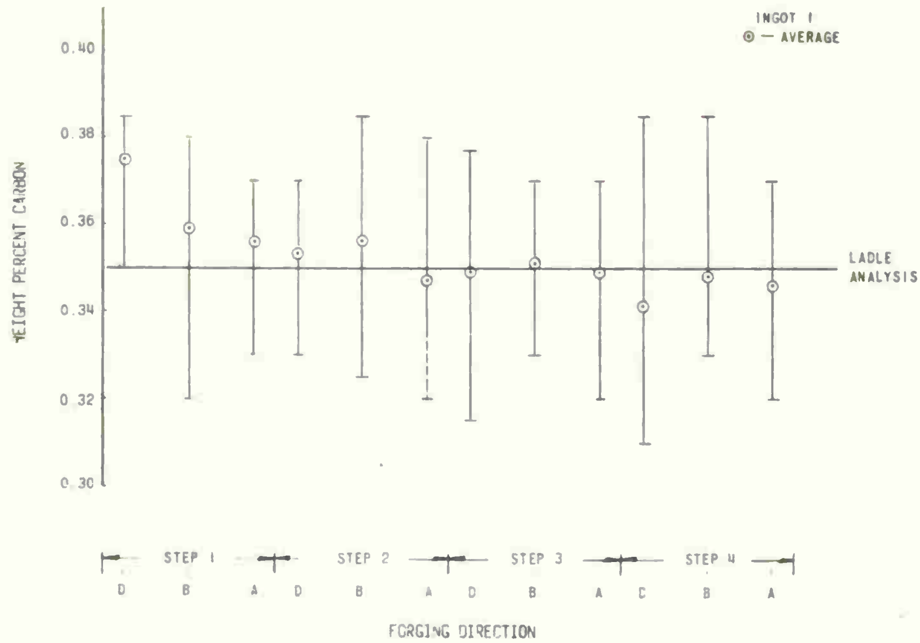

Fig. 14 - Variation of carbon concentration with forging reduction in Ingot No. 1.

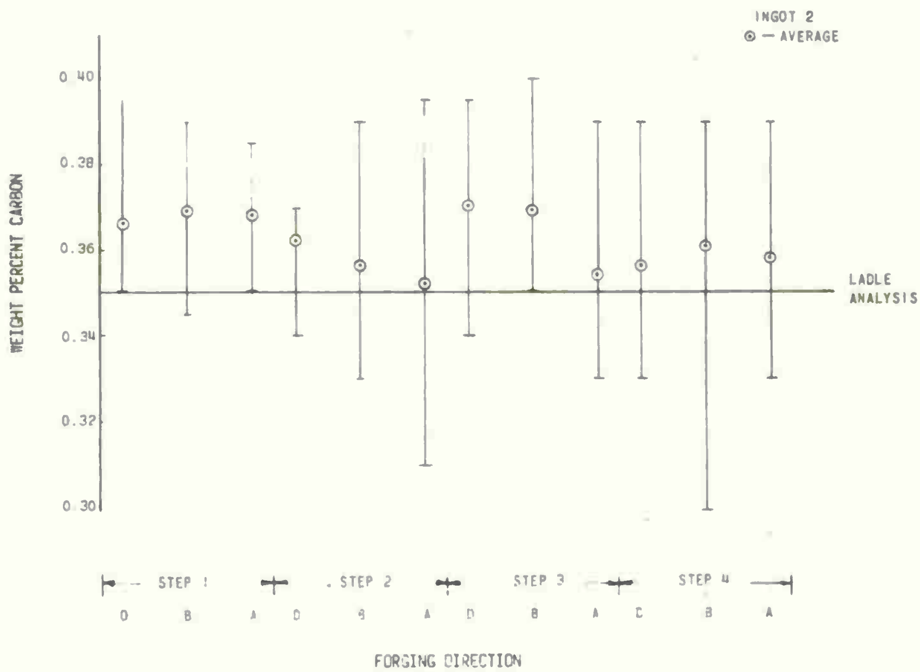

Fig. 15 - Variation of carbon concentration with forging reduction in Ingot No. 2.

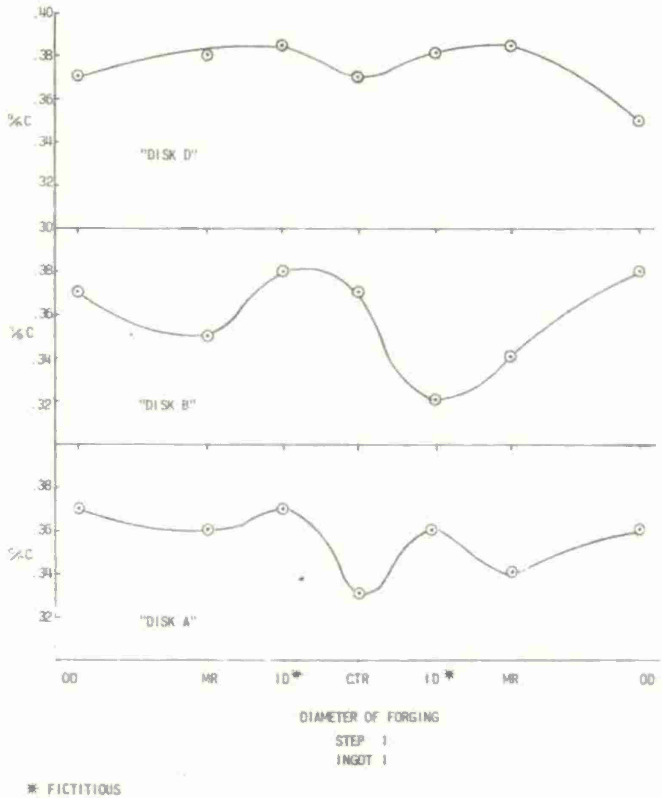

Fig. 16 - Variation of carbon concentration transverse to forging direction. Fictitious ID approximates a bore surface in a gun tube. Step 1, Ingot 1.

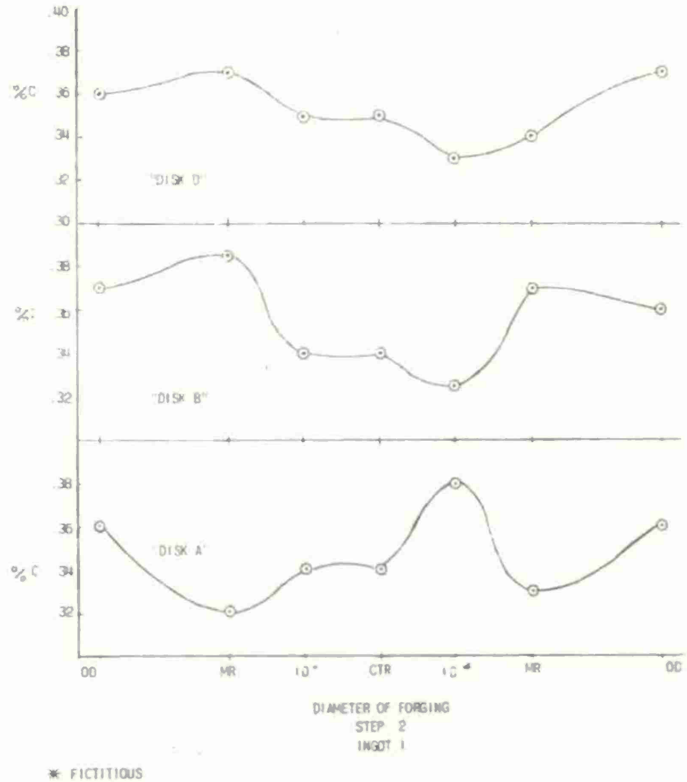

Fig. 17 - Variation of carbon concentration transverse to forging direction. Fictitious ID approximates a bore surface in a gun tube. Step 2, Ingot 1.

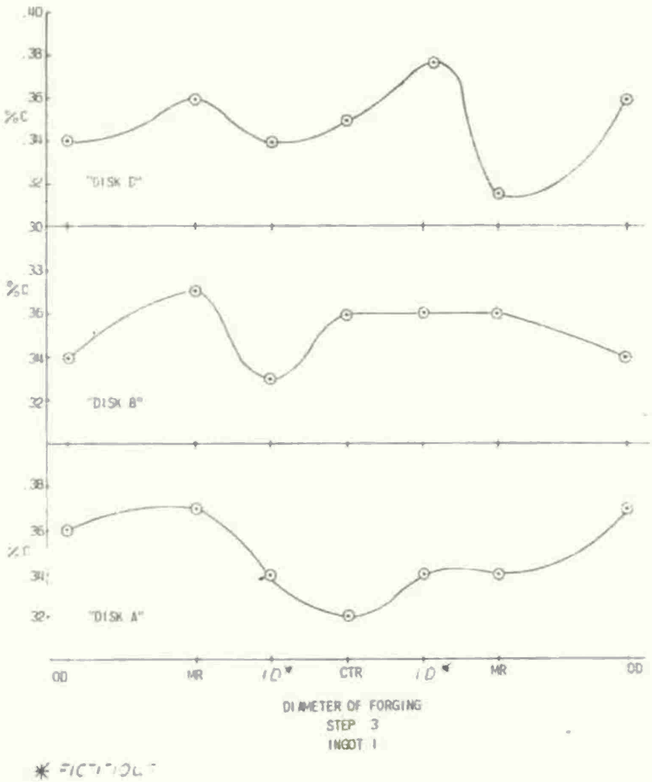

Fig. 18 - Variation of carbon concentration transverse to forging direction. Fictitious ID approximates a bore surface in a gun tube. Step 3, Ingot 1.

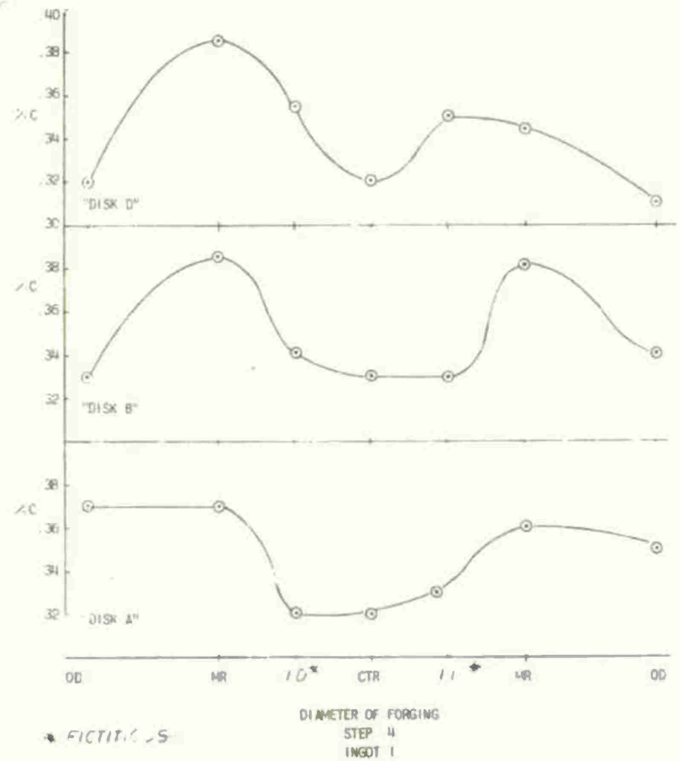

Fig. 19 - Variation of carbon concentration transverse to forging direction. Fictitious ID approximates a bore surface in a gun tube. Step 4, Ingot 1.

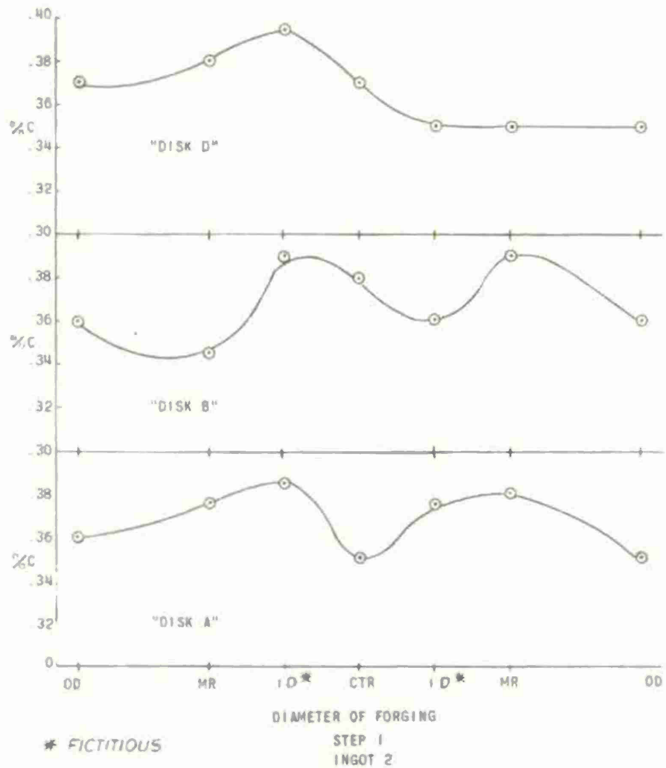

Fig. 20 - Variation of carbon concentration transverse to forging direction. Fictitious ID approximates a bore surface in a gun tube. Step 1, Ingot 2.

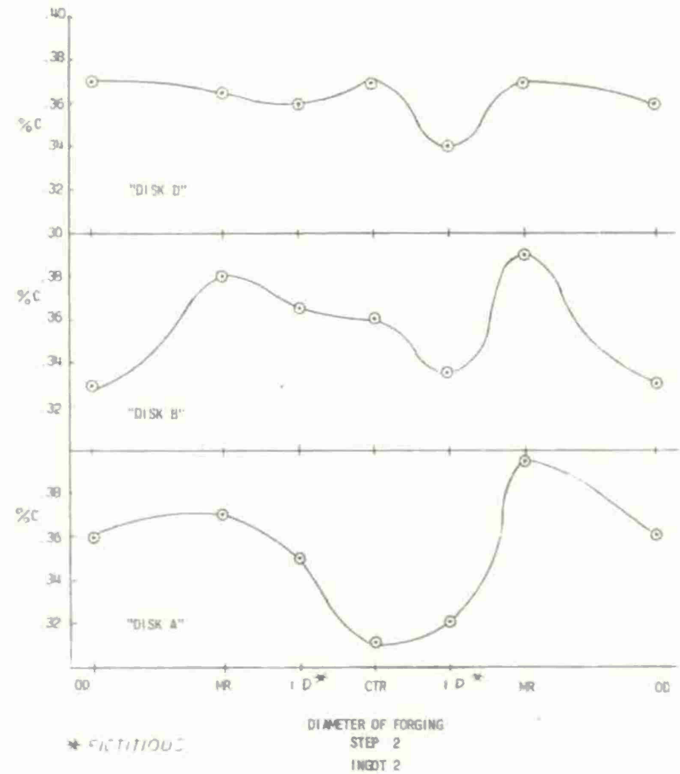

Fig. 21 - Variation of carbon concentration transverse to forging direction. Fictitious ID approximates a bore surface in a gun tube. Step 2, Ingot 2.

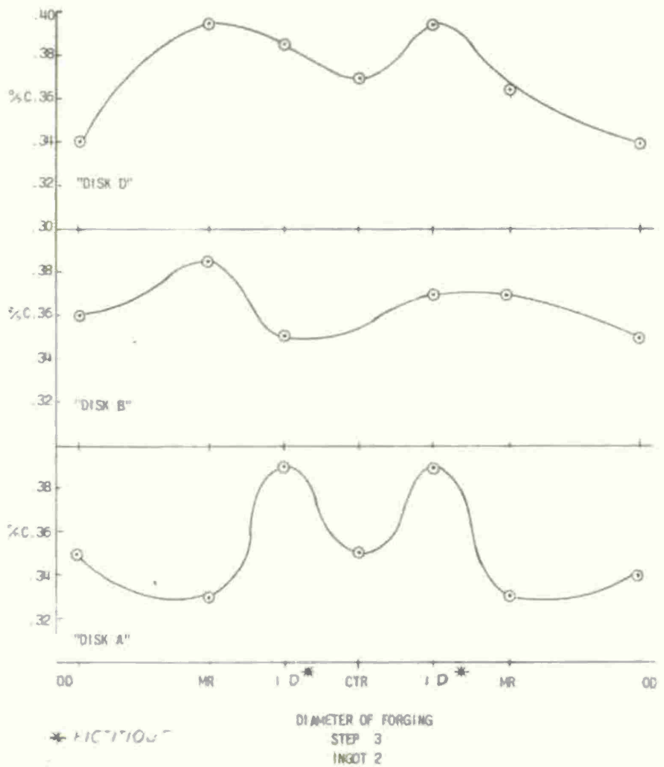

Fig. 22 - Variation of carbon concentration transverse to forging direction. Fictitious ID approximates a bore surface in a gun tube. Step 3, Ingot 2

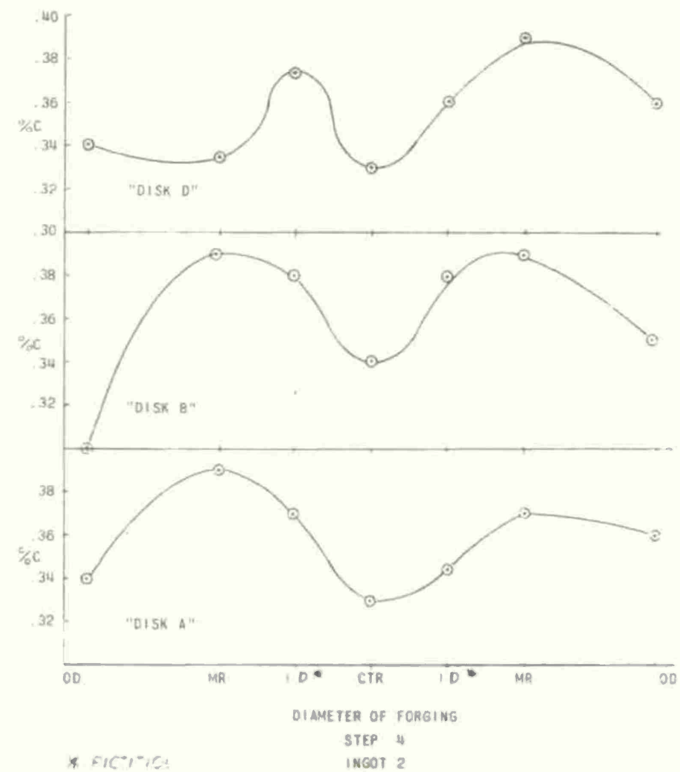

Fig. 23 - Variation of carbon concentration transverse to forging direction. Fictitious ID approximates a bore surface in a gun tube. Step 4, Ingot 2.

from both ingots. Two features are evident. First, there is a general similarity in carbon profile between corresponding disks and steps from Ingots 1 and 2. This indicates that the solidification mechanisms in each ingot are operating in a similar fashion (a reassuring observation). Second and more important is the obvious heterogeneity of carbon concentration across the diameter of some cross sections. In other words, we have a varying alloy from one side of the cylinder to the other. Indubitably, the mechanical properties of the quenched and tempered product will respond with a corresponding variation.

Recapitulating, we have observed statistically significant variation in yield strength, % reduction of area, Charpy impact @ -40°F, and plane strain fracture toughness, due to different reduction ratios within the same forged ingot. In addition, the Charpy impact data also exhibited real variation between identical size ingots poured from the same heat of steel. Moreover, the carbon concentration exhibited statistically significant variation due to both ingots and steps, plus considerable variation within individual disks, revealing a tendency for macro segregation. This may or may not be associated with the differences in concentrations of the other alloying elements, viz., Mn, Cr, Mo. Some elements in steel tend to segregate more readily than others. Sulphur segregates to the greatest extent while the following elements also segregate, but to a somewhat lesser degree in descending order: phosphorous, carbon, silicon and manganese[10].

10. The Making, Shaping and Treating of Steel, United States Steel, 8th Edition, Pittsburgh, Pa., 1964, p. 550.

Chemical inhomogeneities on a macroscopic scale are the result of differences in segregation due to long range transport of matter within an ingot. The complexity of segregation in large ingots is augmented by the fact that the liquid enriched with rejected solute can be moved by five separate effects: (1) The motion of the liquid as it enters the mold, (2) Convection caused by differences of density due to temperature gradients, and (3) Convection caused by differences of density due to variations in composition of the liquid as a result of solute redistribution, (4) Motion caused by gravity, of crystals that are growing in the liquid, and finally, (5) Motion of liquid due to solidification shrinkage[11]. Therefore, the carbon segregation measured in this steel cannot be predicted on just a diffusion or redistribution basis alone. The motion of the fluid during solidification of a large ingot must be considered when analyzing normal and convective segregations of chemical elements.

Conclusions

Considering the results of this investigation in light of the interaction between chemical segregation and mechanical working for this material, we are permitted the following conclusions:

1. An approximate forging reduction ratio of 3:1 produced optimum average values of % RA, Charpy impact and fracture toughness in this material. This data holds for forging reductions produced on ingots where the maximum work was given to the bottom of the ingots. As was previously mentioned, a follow on study is being conducted to investigate the effects of working the top of the ingot to a similar reduction.

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11. Chalmers, B., Principles of Solidification, John Wiley & Sons, Inc., New York, 1964, p. 283

2. Real variation, that is, variation in excess of experimental error variance, was determined in yield strength, % reduction of area, Charpy impact energy and plane strain fracture toughness. This variation occurred between different forging reductions of the same ingot in the range of 1.5:1 to 10:1.

3. Significant variation was also measured in Charpy impact energy due to separate identical size ingots poured from the same heat.

4. Likewise, real variation in carbon concentration was measured due to different forging reductions and separate ingots.

In view of the control exercised on this "full-size" experiment, viz. uniform microstructures, nonmetallic inclusion contents, etc., we must conclude that chemical inhomogeneity, in particular, carbon segregation on a macroscale, is a major contributor to mechanical property variation in the steel produced herein. The mechanical working alters the segregation pattern but in no way eliminates it. This apparently constitutes a solidification problem and the only method of correction is to modify the solidification mechanisms, thereby preventing the flow of solute-rich material. Currently this refinement is being achieved in the electroslag remelting and vacuum arc remelting process. However the ingot size in ESR is presently limited to approximately 20" in diameter.

TABLE 1

ANOVA - 0.1% Yield Strength

Source of Variation	S.S.	D.F.	M.S.	F exp.	F(5%)	Variation
A	6.17	1	6.17	.0032	3.9	Insignificant
B	168,844	3	56,281	29.2	2.7	Significant
C	2,832	2	1,416	0.73	19.5	Insignificant
SSE	62,951	137	1,927			

A - Between Ingots

B - Between Steps (forging reduction)

C - Between disks within a step

SSE - Experimental error term (includes interactions)

TABLE 2

ANOVA - % Reduction of Area

Source of Variation	S.S.	D.F.	M.S.	F exp.	F(5%)	Variation
A	16,256	1	16,256	2.5	3.9	Insignificant
B	166,038	3	55,346	8.5	2.7	Significant
C	2,371	2	1,185	0.2	19.5	Insignificant
SSE	894,973	137	6,533			

A - Between Ingots

B - Between Steps (forging reduction)

C - Between Disks within a step

SSE - Experimental Error term (includes interactions)

TABLE 3

ANOVA - Charpy Impact (ft-lb)

Source of Variation	S.S.	D.F.	M.S.	F exp.	F(5%)	Variation
A	5,476	1	5,476	15.6	3.9	Significant
B	32,446	3	10,815	30.9	2.7	Significant
C	928	2	464	1.3	3.1	Insignificant
SSE	47,893	137	350			

A - Between Ingots

B - Between Steps (forging reduction)

C - Between Disks within a step

SSE - Experimental Error term (includes interactions)

TABLE 4

ANOVA - K_5 Fracture Toughness (ksi-kn$^{1/2}$)

Source of Variation	S.S.	D.F.	M.S.	F exp.	F(5%)	Variation
A	1.6	1	1.6	0.1	252	Insignificant
B	98.4	2	49.2	4.1	3.1	Significant
C	28.9	2	14.4	1.2	3.5	Insignificant
SSE	641.8	54	11.9			

A - Between Ingots

B - Between Steps (forging reduction)

C - Between disks within a step

SSE - Experimental Error term (includes interactions)

TABLE 5

Statistical Variation Summary - Mechanical
(5% Significance Level)

	Source of Variation		
Factor	Ingots	Steps	Disks
.1% Y.S.	I	S	I
% RA	I	S	I
-40° Cr	S	S	I
K_5	I	S	I

S - Significant variation

I - Insignificant variation

TABLE 6

NONMETALLIC INCLUSION ASSESSMENT - VOLUME %

INGOT 1			INGOT 2		
Spec No.	L	T	Spec. No.	L	T
1A1T1	.053	.069	2A1T1	.054	.050
1A1T4	.056	.068	2A1T4	.053	.056
1B1T1	.046	.049	2B1T1	.043	.046
1B1T4	.036	.063	2B1T4	.053	.053
1D1T1	.046	.059	2D1T1	.066	.069
1D1T4	.053	.056	2D1T4	.063	.050
1A2T1	.066	.050	2A2T1	.066	.040
1A2T4	.056	.061	2A2T4	.058	.073
1B2T1	.056	.046	2B2T1	.046	.063
1B2T4	.046	.040	2B2T4	.053	.043
1D2T1	.053	.059	2D2T1	.046	.063
1D2T4	.059	.050	2D2T4	.066	.053
1A3T1	.056	.050	2A3T1	.046	.044
1A3T4	.053	.046	2A3T4	.044	.053
1B3T1	.069	.063	2B3T1	.051	.063
1B3T4	.036	.030	2B3T4	.056	.082
1D3T1	.069	.040	2D3T1	.059	.056
1D3T4	.056	.076	2D3T4	.036	.050
1A4T1	.043	.050	2A4T1	.043	.046
1A4T4	.046	.063	2A4T4	.046	.059
1B4T1	.086	.073	2B4T1	.046	.046
1B4T4	.043	.053	2B4T4	.066	.069
1D4T1	.050	.056	2D4T1	.053	.059
1D4T4	.050	.043	2D4T4	.043	.050

L - longitudinal plane

T - transverse plane

TABLE 7

ANOVA - % C

Source of Variation	S.S.	D.F.	M.S.	F exp.	F(5%)	Variation
A	3,809	1	3,809	9.1	3.9	Significant
B	4,513	3	1,504	3.6	2.7	Significant
C	985	2	493	1.2	3.1	Insignificant
SSE	67,701	161	420			

A - Between Ingots

B - Between Steps (forging reduction)

C - Between Disks within a step

SSE - Experimental Error term (includes interactions)

TABLE 8

ANOVA - % Mn

Source of Variation	S.S.	D.F.	M.S.	F exp.	F(5%)	Variation
A	1,001	1	1,001	1.8	3.9	Insignificant
B	1,021	3	340	0.6	8.5	Insignificant
C	1,161	2	581	1.1	3.1	Insignificant
SSE	87,701	161	545			

A - Between Ingots

B - Between Steps (forging reduction)

C - Between Disks within a step

SSE - Experimental Error term (includes interactions)

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of Mr. W. Lynch during the metallurgical portion of this program.

APPENDIX A

Tensile Data

INGOT #1

Step 1

Code	0.1% YS (ksi)	0.2% YS (ksi)	UTS (ksi)	%El	%RA
1A1T1	178.2	183.0	196.9	15.0	42.4
T2	177.6	183.2	197.1	13.6	35.0
T3	175.0	179.8	194.8	9.3	21.2
T4	177.0	181.2	196.5	8.9	15.57
T5	177.7	182.5	197.3	13.6	38.1
T6	178.0	182.5	197.2	16.0	51.9
1B1T1	179.4	183.6	198.1	14.3	45.8
T2	179.1	183.3	198.0	13.6	42.0
T3	178.6	183.6	197.9	7.9	12.5
T4	177.4	183.1	198.0	10.0	23.2
T5	177.4	182.4	196.8	12.8	40.3
T6	179.5	184.0	198.2	14.7	45.8
1D1T1	179.0	184.4	199.4	13.6	43.6
T2	180.6	185.7	199.7	14.3	45.4
T3	182.2	187.8	202.2	9.3	19.7
T4	180.9	187.8	202.5	11.5	26.5
T5	178.6	183.6	198.4	11.5	31.8
T6	178.5	183.2	197.2	15.0	47.2

Step 2

Code	0.1% YS (ksi)	0.2% YS (ksi)	UTS (ksi)	%El	%RA
1A2T1	174.9	180.8	196.0	13.6	54.2
T2	176.5	182.1	197.0	13.2	40.3
T3	172.6	177.6	192.4	12.1	36.8
T4	172.0	177.4	192.6	14.3	39.0
T5	178.2	183.6	198.5	13.6	40.3
T6	177.4	182.4	196.6	17.1	54.8
1B2T1	178.9	183.1	197.4	16.0	51.6
T2	179.8	184.0	197.7	15.7	47.0
T3	176.2	180.7	195.3	14.6	39.8
T4	174.7	179.8	194.0	12.8	35.4
T5	177.6	182.7	197.0	15.0	47.0
T6	179.5	183.4	197.4	15.7	51.6
1D2T1	178.3	183.1	197.2	17.9	55.5
T2	177.1	182.5	196.6	14.3	47.8
T3	177.0	181.4	196.0	13.6	36.6
T4	176.8	182.2	196.6	12.8	36.3
T5	177.3	182.7	197.4	14.3	40.0
T6	181.3	185.8	199.1	16.1	53.8

INGOT #1

Step 3

Code	0.1% YS (ksi)	0.2% YS (ksi)	UTS (ksi)	%El	%RA
1A3T1	180.0	183.6	198.8	16.0	53.2
T2	177.6	181.6	196.7	17.9	43.5
T3	173.8	179.1	192.9	17.9	47.2
T4	175.2	180.3	194.8	14.3	39.0
T5	178.3	182.8	197.4	15.4	42.4
T6	180.9	184.7	199.5	15.4	48.6
1B3T1	180.6	184.5	199.6	15.7	52.3
T2	180.1	184.9	199.3	15.0	42.4
T3	174.6	178.9	194.4	14.6	42.4
T4	174.6	178.5	193.8	14.0	42.4
T5	180.9	185.2	199.4	15.7	42.8
T6	180.4	185.1	199.2	16.4	50.2
1D3T1	180.9	184.7	199.3	16.0	52.3
T2	179.1	183.2	198.1	15.0	49.8
T3	175.2	180.6	195.8	13.6	42.4
T4	177.1	180.9	195.5	14.3	43.3
T5	179.2	183.4	198.2	14.3	45.4
T6	181.4	185.1	199.1	15.0	51.4

Step 4

Code	0.1% YS (ksi)	0.2% YS (ksi)	UTS (ksi)	%El	%RA
1A4T1	172.9	176.4	189.8	15.0	44.4
T2	171.1	174.4	187.2	16.4	41.0
T3	168.4	173.1	186.4	15.7	41.8
T4	170.2	173.5	186.6	15.0	39.6
T5	170.5	174.1	187.3	15.4	40.3
T6	171.1	174.9	188.2	16.0	46.2
1B4T1	170.8	175.3	188.6	16.0	46.2
T2	173.2	176.4	189.6	16.0	45.2
T3	168.1	172.6	185.8	15.4	42.0
T4	168.6	173.2	187.0	15.0	35.8
T5	171.4	175.6	188.5	15.0	44.1
T6	171.1	175.9	189.0	15.7	45.8
1D4T1	171.5	175.6	189.1	14.3	41.5
T2	163.8	168.0	181.3	15.0	43.6
T3	167.4	171.7	184.9	13.6	40.7
T4	169.3	173.2	185.8	15.0	40.0
T5	170.8	174.7	188.0	14.3	42.6
T6	172.0	175.9	189.2	15.0	43.6

INGOT #2

Step 1

Code	0.1% YS (ksi)	0.2% YS (ksi)	UTS (ksi)	% El	%RA
2A1T1	180.1	184.3	198.0	15.7	49.4
T2	177.4	182.2	197.3	13.6	45.4
T3	174.4	179.8	195.4	7.2	11.7
T4	177.1	182.2	197.2	10.0	17.7
T5	176.4	182.2	197.6	15.7	44.4
T6	179.8	183.7	197.9	15.4	48.4
2B1T1	177.1	182.5	197.6	16.0	51.0
T2	177.4	182.5	197.0	15.7	35.0
T3	178.3	183.3	198.4	15.0	28.5
T4	177.9	183.5	198.3	12.4	31.5
T5	178.9	183.4	197.9	14.0	42.0
T6	179.5	183.7	198.2	14.6	47.4
2D1T1	179.5	183.7	197.9	14.6	46.6
T2	179.0	184.1	198.5	14.3	43.6
T3	180.4	186.5	201.9	11.8	25.4
T4	180.4	186.1	201.3	10.4	23.2
T5	178.5	183.6	198.4	14.3	46.6
T6	179.5	184.3	198.1	15.7	48.8

Step 2

Code	0.1% YS (ksi)	0.2% YS (ksi)	UTS (ksi)	% El	%RA
2A2T1	177.4	181.8	196.9	16.4	53.0
T2	176.4	181.3	196.8	14.3	44.1
T3	173.2	178.3	193.1	12.1	33.2
T4	172.3	177.6	193.1	13.6	39.8
T5	177.4	182.1	196.6	11.5	32.4
T6	178.6	182.8	197.2	16.4	50.6
2B2T1	179.5	183.4	197.5	16.0	52.9
T2	170.2	176.1	190.8	12.1	31.8
T3	175.0	180.0	194.7	14.6	38.2
T4	174.1	179.5	194.0	13.6	37.7
T5	177.8	182.3	196.9	14.3	43.6
T6	178.0	182.2	196.5	16.4	55.1
2D2T1	180.1	184.3	197.6	15.0	48.0
T2	178.9	183.6	197.5	13.2	42.0
T3	175.6	180.0	196.4	13.2	36.0
T4	175.8	181.6	197.8	13.6	40.3
T5	176.2	181.0	196.5	14.3	41.6
T6	179.8	183.6	197.6	15.4	51.0

INGOT #2

Step 3

Code	0.1% YS (ksi)	0.2% YS (ksi)	UTS (ksi)	% El	%RA
2A3T1	179.5	183.1	197.6	15.7	47.0
T2	179.4	184.2	198.8	12.4	36.8
T3	177.3	181.6	196.6	14.3	42.9
T4	176.4	180.9	195.9	13.6	40.0
T5	178.2	183.0	198.0	13.6	41.2
T6	181.5	185.7	199.3	15.7	49.8
2B3T1	179.5	183.4	198.3	15.4	49.0
T2	180.1	184.0	198.0	14.3	43.6
T3	176.1	180.4	195.5	13.6	37.2
T4	177.7	182.2	196.3	13.6	39.0
T5	179.5	183.7	198.2	15.7	45.6
T6	180.4	184.9	198.3	15.7	48.8
2D3T1	180.3	184.7	199.3	16.4	53.6
T2	180.3	183.9	198.0	15.4	47.7
T3	176.5	181.3	196.6	11.8	27.5
T4	177.1	181.8	197.3	13.6	39.0
T5	180.3	183.6	198.2	14.3	44.5
T6	179.4	184.2	199.1	14.3	46.2

Step 4

Code	0.1% YS (ksi)	0.2% YS (ksi)	UTS (ksi)	% El	%RA
2A4T1	173.5	176.8	189.1	15.7	44.6
T2	171.3	174.4	187.4	13.6	39.1
T3	167.5	172.0	185.7	13.2	30.0
T4	168.1	172.3	185.1	12.8	33.8
T5	170.8	174.7	187.5	12.1	28.2
T6	171.1	176.2	189.8	15.0	42.0
2B4T1	172.9	176.2	189.7	14.0	40.7
T2	171.9	176.1	189.0	12.8	35.7
T3	165.7	170.1	182.4	12.1	34.0
T4	168.7	173.4	187.2	12.4	31.3
T5	173.1	176.2	188.5	12.1	29.2
T6	173.2	177.1	189.7	14.3	41.6
2D4T1	172.9	176.2	188.7	13.2	34.8
T2	169.8	174.0	187.0	12.4	37.5
T3	169.9	174.9	186.3	11.5	27.5
T4	168.0	173.2	186.5	12.8	31.7
T5	167.6	172.3	186.3	12.8	35.9
T6	169.9	174.4	188.6	14.3	43.0

APPENDIX B

Charpy Impact Data (-40°F ft-lb)

Step 1

	1A1	1B1	1D1	2A1	2B1	2D1
C1	24.5	24.9	23.3	23.3	23.1	20.9
C2	19.8	21.4	21.4	19.9	21.2	17.5
C3	19.2	19.6	16.5	19.9	18.0	17.5
C4	21.2	19.0	16.3	20.9	17.2	20.9
C5	21.5	20.0	22.1	20.5	20.6	21.8
C6	23.0	22.1	20.9	23.3	24.1	22.7

Step 2

	1A2	1B2	1D2	2A2	2B2	2D2
C1	25.2	23.8	24.8	21.1	20.7	21.3
C2	21.1	21.4	20.5	21.8	22.9	21.1
C3	23.2	21.7	20.0	21.3	20.7	20.2
C4	25.0	24.5	20.0	19.1	21.3	16.8
C5	19.8	21.9	21.6	20.9	19.8	18.1
C6	24.9	26.1	25.5	22.9	23.4	20.5

Step 3

	1A3	1B3	1D3	2A3	2B3	2D3
C1	23.2	20.7	22.6	19.2	19.2	20.3
C2	21.8	19.9	21.3	17.0	20.2	19.2
C3	19.2	22.0	19.8	17.9	16.9	18.3
C4	22.2	21.4	17.0	17.4	18.7	16.2
C5	22.3	17.8	25.9	18.1	18.6	20.7
C6	22.0	21.2	20.9	20.2	19.9	21.8

Step 4

	1A4	1B4	1D4	2A4	2B4	2D4
C1	23.2	23.2	25.2	23.0	25.0	22.5
C2	25.2	23.6	23.8	24.2	23.8	23.9
C3	24.8	23.2	25.1	26.2	22.1	23.8
C4	24.9	22.9	25.8	25.9	22.5	27.0
C5	24.5	24.0	23.0	23.2	23.2	22.1
C6	25.0	22.9	25.8	22.8	24.8	23.2

APPENDIX C

K_5 Fracture Toughness Data (ksi-in$^{1/2}$)

Step 1

	1A1	1B1	1D1	2A1	2B1	2D1
1	118	121	116	124	120	123
2	119	117	116	118	117	122
3	125	122	117	128	120	122
4	122	115	121	122	121	122

Step 2

	1A2	1B2	1D2	2A2	2B2	2D2
1	*	122	121	120	130	127
2	126	121	123	116	118	125
3	126	126	127	124	120	116
4	123	125	121	126	125	120

Step 3

	1A3	1B3	1D3	2A3	2B3	2D3
1	121	122	125	122	114	118
2	126	123	117	118	117	123

Step 4

	1A4	1B4	1D4	2A4	2B4	2D4
1	113	111	*	114	111	115
2	118	111	113	113	116	124

*Test invalid

APPENDIX D

CHEMICAL ANALYSIS

STEP 1, INGOT 1

SPECIMEN	C	Mn	P	S	Si	Ni	Cr	Mo	V
1D1 C1	.37	.44	.010	.007	.25	3.13	.94	.69	.11
1D1 C2	.38	.42		.009	.26	3.00	.92	.67	.11
1D1 C3	.385	.43		.008	.26	3.06	.92	.67	.11
1D1 CTR	.37	.40	.011	.005	.27	3.10	.92	.66	.11
1D1 C4	.382	.43		.005	.26	3.07	.93	.68	.11
1D1 C5	.385	.39		.006	.26	2.98	.92	.66	.10
1D1 C6	.35	.42	.009	.007	.27	3.16	.92	.68	.11
1B1 C1	.37	.42	.010	.007	.27	3.06	.92	.69	.11
1B1 C2	.35	.39		.009	.25	3.00	.93	.65	.11
1B1 C3	.38	.37		.005	.24	3.04	.92	.65	.11
1B1 CTR	.37	.41	.012	.005	.27	3.11	.92	.60	.11
1B1 C4	.32	.35	.	.006	.23	3.05	.90	.62	.10
1B1 C5	.34	.40		.005	.25	3.05	.94	.65	.11
1B1 C6	.38	.39	.008	.007	.25	3.04	.91	.67	.10
1A1 C1	.37	.39	.009	.007	.25	2.95	.91	.66	.10
1A1 C2	.36	.39		.009	.26	2.96	.92	.67	.11
1A1 C3	.37	.38		.008	.25	2.94	.92	.62	.11
1A1 CTR	.33	.38	.010	.005	.26	3.10	.91	.64	.11
1A1 C4	.36	.40		.005	.23	2.92	.93	.64	.11
1A1 C5	.34	.39		.008	.27	2.96	.93	.64	.11
1A1 C6	.36	.39	.010	.007	.23	2.88	.91	.64	.10

STEP 1, INGOT 2

SPECIMEN	C	Mn	P	S	Si	Ni	Cr	Mo	V
2D1 C1	.37	.43	.009	.006	.26	3.11	.92	.67	.11
2D1 C2	.38	.38			.26	3.15	.90	.66	.10
2D1 C3	.395	.44			.26	3.14	.92	.69	.11
2D1 CTR	.37	.42	.010	.005	.23	2.84	.98	.64	.11
2D1 C4	.35	.40			.25	3.09	.92	.65	.11
2D1 C5	.35	.40			.26	3.09	.92	.65	.11
2D1 C6	.35	.42	.008	.006	.26	3.14	.92	.68	.11
2B1 C1	.36	.42	.012	.007	.26	3.04	.91	.66	.10
2B1 C2	.345	.41			.24	2.96	.92	.64	.10
2B1 C3	.39	.42			.25	2.98	.94	.69	.11
2B1 CTR	.38	.39	.011	.003	.26	3.14	.94	.67	.11
2B1 C4	.36	.40			.25	3.03	.92	.63	.10
2B1 C5	.39	.43			.22	2.92	.95	.66	.11
2B1 C6	.36	.42	.011	.007	.26	2.91	.91	.68	.10
2A1 C1	.36	.39	.010	.007	.25	2.98	.92	.67	.10
2A1 C2	.375	.42			.26	3.04	.95	.68	.10
2A1 C3	.385	.42			.26	3.08	.92	.67	.10
2A1 CTR	.35	.39	.010	.002	.26	3.14	.92	.64	.12
2A1 C4	.375	.42			.26	3.00	.93	.67	.10
2A1 C5	.38	.42			.26	3.08	.93	.68	.10
2A1 C6	.35	.42	.009	.007	.26	3.11	.95	.72	.11

STEP 2, INGOT 1

SPECIMEN	C	Mn	P	S	Si	Ni	Cr	Mo	V
1D2 C1	.36	.41	.008	.006	.29	3.00	.94	.65	.11
1D2 C2	.37	.40			.26	3.10	.93	.68	.11
1D2 C3	.35	.40			.26	3.03	.92	.67	.10
1D2 CTR	.35	.43	.010	.004	.26	3.04	.96	.67	.12
1D2 C4	.33	.40			.26	3.10	.90	.66	.10
1D2 C5	.34	.40			.26	3.10	.92	.66	.11
1D2 C6	.37	.44	.009	.006	.26	3.07	.95	.66	.11
1B2 C1	.37	.40	.011	.007	.24	2.94	.93	.66	.11
1B2 C2	.385	.40			.26	3.00	.94	.66	.11
1B2 C3	.34	.40			.25	2.99	.91	.65	.10
1B2 CTR	.34	.44	.010	.011	.26	3.00	.98	.68	.12
1B2 C4	.325	.39			.25	3.00	.91	.64	.10
1B2 C5	.37	.42			.27	3.05	.92	.68	.11
1B2 C6	.36	.43	.009	.009	.26	3.10	.95	.69	.12
1A2 C1	.36	.46	.009	.008	.26	2.91	.97	.68	.11
1A2 C2	.32	.40			.27	3.10	.95	.68	.11
1A2 C3	.34	.37			.25	2.96	.90	.61	.10
1A2 CTR	.34	.35	.008	.004	.25	3.12	.91	.61	.11
1A2 C4	.38	.40			.27	3.10	.90	.66	.11
1A2 C5	.33	.39			.27	3.09	.93	.64	.11
1A2 C6	.36	.39	.010	.007	.25	2.94	.92	.66	.11

STEP 2, INGOT 2

SPECIMEN	C	Mn	P	S	Si	Ni	Cr	Mo	V
2D2 C1	.37	.47	.008	.007	.28	3.19	.93	.66	.13
2D2 C2	.365	.39			.25	3.05	.90	.64	.10
2D2 C3	.36	.37			.24	3.14	.93	.66	.10
2D2 CTR	.37	.39	.009	.005	.25	3.09	.93	.63	.11
2D2 C4	.34	.39			.26	3.15	.92	.64	.10
2D2 C5	.37	.38			.26	3.18	.93	.68	.11
2D2 C6	.36	.47	.007	.006	.27	3.23	.95	.67	.12
2B2 C1	.33	.40	.009	.006	.24	2.91	.92	.63	.10
2B2 C2	.38	.43			.25	3.06	.93	.65	.11
2B2 C3	.365	.41			.26	3.09	.93	.65	.11
2B2 CTR	.36	.40	.010	.003	.25	3.03	.93	.63	.11
2B2 C4	.335	.38			.23	2.95	.93	.61	.10
2B2 C5	.39	.38			.24	3.03	.92	.66	.10
2B2 C6	.33	.44	.009	.007	.24	2.90	.94	.61	.11
2A2 C1	.36	.39	.008	.007	.23	2.89	.92	.65	.10
2A2 C2	.37	.39			.25	3.00	.93	.63	.11
2A2 C3	.35	.41			.26	2.99	.91	.64	.11
2A2 CTR	.31	.37	.009	.003	.22	2.99	.92	.59	.10
2A2 C4	.32	.40			.26	3.03	.93	.65	.11
2A2 C5	.395	.39			.25	2.99	.94	.63	.11
2A2 C6	.36	.48	.009	.009	.27	3.01	.96	.66	.12

STEP 3 INGOT 1

SPECIMEN	C	Mn	P	S	Si	Ni	Cr	Mo	V
1D3 C1	.34	.43	.010	.007	.27	3.04	.95	.68	.11
1D3 C2	.36	.38			.25	2.96	.93	.65	.10
1D3 C3	.34	.37			.24	2.96	.91	.60	.10
1D3 CTR	.35	.36	.012	.007	.26	3.10	.90	.66	.11
1D3 C4	.377	.38			.25	3.00	.92	.63	.10
1D3 C5	.315	.37			.24	3.00	.92	.62	.10
1D3 C6	.36	.40	.010	.007	.26	3.09	.95	.68	.11
1B3 C1	.34	.41	.009	.005	.26	2.93	.93	.66	.11
1B3 C2	.37	.39			.25	3.05	.93	.64	.11
1B3 C3	.33	.39			.25	3.06	.92	.64	.11
1B3 CTR	.36	.35	.011	.010	.25	3.06	.89	.65	.11
1B3 C4	.36	.38			.24	3.10	.91	.65	.11
1B3 C5	.36	.40			.25	3.10	.94	.66	.11
1B3 C6	.34	.40	.008	.006	.25	2.89	.90	.64	.11
1A3 C1	.36	.45	.009	.007	.24	2.79	.96	.66	.11
1A3 C2	.37	.45			.26	3.06	.93	.67	.11
1A3 C3	.34	.42			.24	3.06	.92	.63	.10
1A3 CTR	.32	.35	.010	.006	.25	2.97	.90	.63	.10
1A3 C4	.34	.42			.24	3.06	.92	.62	.10
1A3 C5	.34	.42			.25	3.07	.94	.66	.11
1A3 C6	.37	.43	.010	.0097	.25	2.76	.96	.66	.11

STEP 3 INGOT 2

SPECIMEN	C	Mn	P	S	Si	Ni	Cr	Mo	V
2D3 C1	.34	.44	.007	.005	.27	3.09	.91	.64	.12
2D3 C2	.395	.38			.26	3.14	.91	.66	.10
2D3 C3	.385	.40			.27	3.20	.92	.69	.11
2D3 CTR	.37	.36	.009	.005	.26	3.08	.90	.66	.11
2D3 C4	.395	.40			.27	3.16	.91	.68	.11
2D3 C5	.365	.39			.27	3.19	.94	.68	.11
2D3 C6	.34	.43	.008	.005	.28	3.15	.92	.66	.11
2B3 C1	.36	.39	.009	.007	.25	2.94	.92	.66	.10
2B3 C2	.385	.38			.21	3.02	.91	.60	.10
2B3 C3	.35	.42			.24	3.00	.92	.64	.10
2B3 CTR	.40	.36	.010	.007	.26	2.94	.90	.64	.10
2B3 C4	.37	.39			.25	3.02	.90	.63	.10
2B3 C5	.37	.40			.25	3.06	.90	.64	.10
2B3 C6	.35	.43	.011	.007	.25	3.00	.92	.66	.10
2A3 C1	.35	.45	.007	.005	.26	2.85	.96	.67	.11
2A3 C2	.33	.42			.26	3.05	.92	.68	.11
2A3 C3	.39	.43			.26	3.03	.93	.68	.11
2A3 CTR	.35	.35	.008	.006	.25	3.03	.90	.66	.11
2A3 C4	.39	.41			.25	3.05	.93	.68	.11
2A3 C5	.33	.41			.26	3.07	.93	.68	.11
2A3 C6	.34	.43	.010	.006	.27	2.96	.95	.66	.11

STEP 4 INGOT 1

SPECIMEN	C	Mn	P	S	Si	Ni	Cr	Mo	V
1D4 C1	.32	.38	.009	.005	.25	3.11	.95	.65	.11
1D4 C2	.385	.39			.25	3.06	.93	.65	.10
1D4 C3	.355	.36			.24	3.04	.92	.64	.10
1D4 CTR	.32	.42	.012	.007	.25	3.09	.91	.65	.10
1D4 C4	.35	.40			.26	3.10	.96	.68	.11
1D4 C5	.344	.39			.25	3.01	.93	.66	.10
1D4 C6	.31	.38	.008	.004	.25	3.11	.94	.66	.11
1B4 C1	.33	.39	.008	.004	.25	2.88	.95	.64	.11
1B4 C2	.385	.40			.25	2.97	.94	.65	.10
1B4 C3	.34	.38			.25	2.98	.93	.65	.10
1B4 CTR	.33	.43	.012	.009	.25	3.00	.91	.65	.10
1B4 C4	.33	.39			.25	3.05	.93	.64	.10
1B4 C5	.382	.39			.25	2.99	.93	.65	.10
1B4 C6	.34	.42	.008	.005	.25	3.10	.96	.66	.11
1A4 C1	.37	.41	.010	.005	.26	3.16	.95	.64	.11
1A4 C2	.37	.40			.23	3.00	.91	.63	.10
1A4 C3	.32	.44			.25	3.12	.94	.67	.11
1A4 CTR	.32	.43	.012	.012	.25	3.06	.91	.65	.10
1A4 C4	.33	.41			.24	3.05	.92	.66	.10
1A4 C5	.36	.42			.25	3.11	.92	.65	.11
1A4 C6	.35	.40	.009	.006	.26	3.18	.93	.65	.11

STEP 4 INGOT 2

SPECIMEN	C	Mn	P	S	Si	Ni	Cr	Mo	V
2D4 C1	.34	.43	.007	.004	.28	3.16	.96	.62	.11
2D4 C2	.335	.38			.27	3.15	.92	.68	.11
2D4 C3	.375	.38			.27	3.13	.91	.68	.10
2D4 CTR	.33	.42	.012	.008	.28	3.07	.91	.69	.10
2D4 C4	.36	.37			.27	3.04	.91	.66	.10
2D4 C5	.39	.39			.27	3.06	.92	.68	.11
2D4 C6	.36	.40	.007	.004	.25	3.03	.94	.60	.11
2B4 C1	.30	.39	.008	.004	.26	3.09	.95	.62	.11
2B4 C2	.39	.39			.26	3.10	.92	.68	.11
2B4 C3	.38	.38			.25	3.14	.90	.67	.10
2B4 CTR	.34	.43	.013	.006	.25	3.12	.91	.68	.10
2B4 C4	.38	.39			.26	3.10	.91	.66	.10
2B4 C5	.39	.43			.26	3.14	.92	.68	.11
2B4 C6	.35	.40	.007	.004	.27	3.13	.94	.64	.11
2A4 C1	.34	.43	.008	.004	.28	3.16	.96	.62	.11
2A4 C2	.39	.40			.24	3.03	.92	.68	.11
2A4 C3	.37	.40			.24	3.00	.91	.67	.10
2A4 CTR	.33	.42	.010	.008	.25	3.07	.91	.69	.10
2A4 C4	.345	.39			.23	3.00	.90	.61	.10
2A4 C5	.37	.41			.25	3.10	.91	.64	.10
2A4 C6	.36	.40	.008	.004	.25	3.03	.94	.60	.11

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